Chapter 14. The Tucannon Salmon

System dynamics may be used to help policy makers and environmental managers improve their instinctive understanding of dynamic behavior. This chapter illustrates how this may be done with a simulation model of the salmon population of the Tucannon River. The model simulates the long term trends in the population over successive generations. The model is then used to simulate the impact of land use development, hydro electric development and harvesting. The Tucannon model illustrates the value of building more than one model of the same system. As a long term model of the entire population, it serves as a natural accompaniment to the short term model from the previous chapter.

This chapter demonstrates how simulation might be used in fishery management. Fisheries have declined in the northwest and around the world. You will learn how previous simulation models have been used to help managers deal with the many factors contributing to the decline. This chapter concludes with exercises to apply and improve the Tucannon model. It also includes an interactive exercise to place you in the role of fishery manager.

Background

The Tucannon rises in the Blue Mountains and flows toward the Snake River, as shown in Figure 14.1. About 50 miles are suitable for Chinook salmon or steelhead trout habitat, and each mile supports around 65 redds. (A redd is the spawning nest formed in the gravel.) Each redd contains

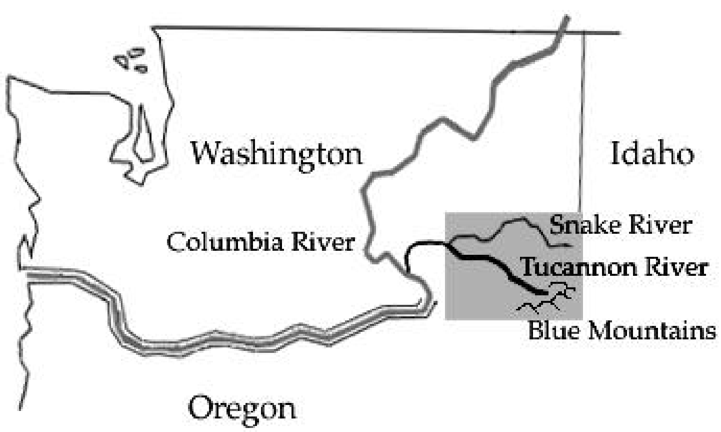


Figure 14.1 Location of the Tucannon River.

thousands of eggs which hatch in the spring. The hatchlings live for a month or more on nutrients stored in their yolk sacs. Once the sac is absorbed, the young fish (called fry) must find and capture food. The juveniles spend a year in the Tucannon competing for food. Those that survive undergo a biochemical change called smoltification that triggers the migration urge. The smolts migrate around 50 miles to reach the Snake River. The remainder of the trip down the Snake and Columbia is around 400 miles. You have read about the challenges in the spring migration in the previous chapter, so you know that many of the smolts will die before reaching the ocean.

The ocean provides the larger and more abundant food that the salmon require to grow to maturity. They spend two years in the ocean and return to the mouth of the Columbia in the spring of their final year. They migrate up the Columbia and Snake rivers to reach the mouth of the Tucannon. (Experts are not sure, but it is believed that they find their way by distinguishing minute differences in the chemical composition of the streams along the way.) They reach the spawning grounds in the fall to build the redds for the next generation.

The Tucannon habitat has been studied by Bjornn (1987) in research for the US Soil Conservation Service. He developed estimates of various population parameters and combined the parameters in a spread sheet model to project changes in the population from one generation to the next. He used the spread sheet to find the harvest that would be possible if the population were managed to achieve maximum sustained yield. With predevelopment assumptions, Bjornn calculated that around 20,000 adults could return to the mouth of the Columbia each year and that 13,000 could be harvested in a sustainable manner.

By northwest standards, the Tucannon is a small river. (The entire basin covers only 210,000 acres.) So you might be skeptical about 20 thousand fish returning to such a small river. To gain some perspective, let's amplify the Tucannon estimate based on the relative size of the watershed. The entire Columbia River Basin is around 800 times larger than the Tucannon, so let's amplify the 20 thousand returning adults to obtain an estimate of adults returning for the entire basin. The result staggers the mind:

**around 16 million salmon would return
to the mouth of the Columbia every year!**

Such a migration is hard to comprehend with current conditions on the river. Nevertheless, our best information from the era prior to development suggests that around 16 million salmon and steelhead actually migrated back to the Columbia each year (EIS 1992, p. 1-6).

Bjornn used the spread sheet model to find the maximum sustainable harvest under conditions in the 1970s. Development was represented by changes in the habitat parameters (due to land use development) and by changes in migration parameters (due to hydroelectric development). His calculations revealed that around 2,400 adults could return to the Columbia, and around 600 could be harvested in a sustainable manner.

Bjornn's analysis suggests that development has reduced the overall size of the fishery by around ten to twenty fold. You should know that a twenty fold reduction is not out of line with trends in the Columbia River Basin. The Columbia river salmon and steelhead runs have been impacted by a combination of factors including harvesting, dams, irrigation, mining, and livestock grazing. Before any of these impacts, up to 16 million wild salmon and steelhead returned to spawn in the streams where they were born (EIS 1992, p. 1-6). By 1938, the year when the Bonnevile Dam was completed, the number of returning adults had fallen to 5 or 6 million, due to a combination of overfishing and upstream activities that blocked spawning access or degraded habitat. By the end of the 1980s, the total was "around 2.5 million, including known fish harvested in the ocean, with about 0.5 million of these as wild fish" (EIS 1992, p. 1-6).

Purpose and Reference Mode

The purpose of the model is to simulate the long term trends in the salmon population over several decades. We will initialize the model with a small number of fish. The initial conditions could represent a small number that found their way to the Tucannon in the era prior to development. They would discover suitable conditions for growth, and our instincts tell us that they would probably grow from one generation to the next until their numbers reached a limit on the Tucannon. Given the fundamental patterns in Chapter 1, our best choice for a reference mode is "S Shaped Growth." Our initial objective, therefore, is to develop a model which simulates S shaped growth in the salmon population under predevelopment conditions. We will check the equilibrium population with the corresponding estimates by Bjornn. Then we can use the model to look at the impact of land use development, hydro-electric development and harvesting.

Model Design

The model is designed with seven stocks to keep track of the population in various phases of the life cycle, as shown in Figure 14.2. The salmon move through the phases in tightly controlled patterns, so it makes good sense to use conveyors. The seven conveyors are assigned the following transit times:

adults about to spawn	1 month
eggs in redds	6 months
juveniles in Tucannon	12 months
smolts in migration	1 month
one yr olds in ocean	12 months
two yr olds in ocean	12 months
adults in migration	4 months

The life cycle begins in the fall when spawners build the redds. The eggs hatch 6 months later. The juveniles need 12 months to grow into smolts; the smolts need 1 month to reach the ocean. After two years in the ocean, they return to the Columbia where their upstream migration requires 4 months. The total life cycle is four years.

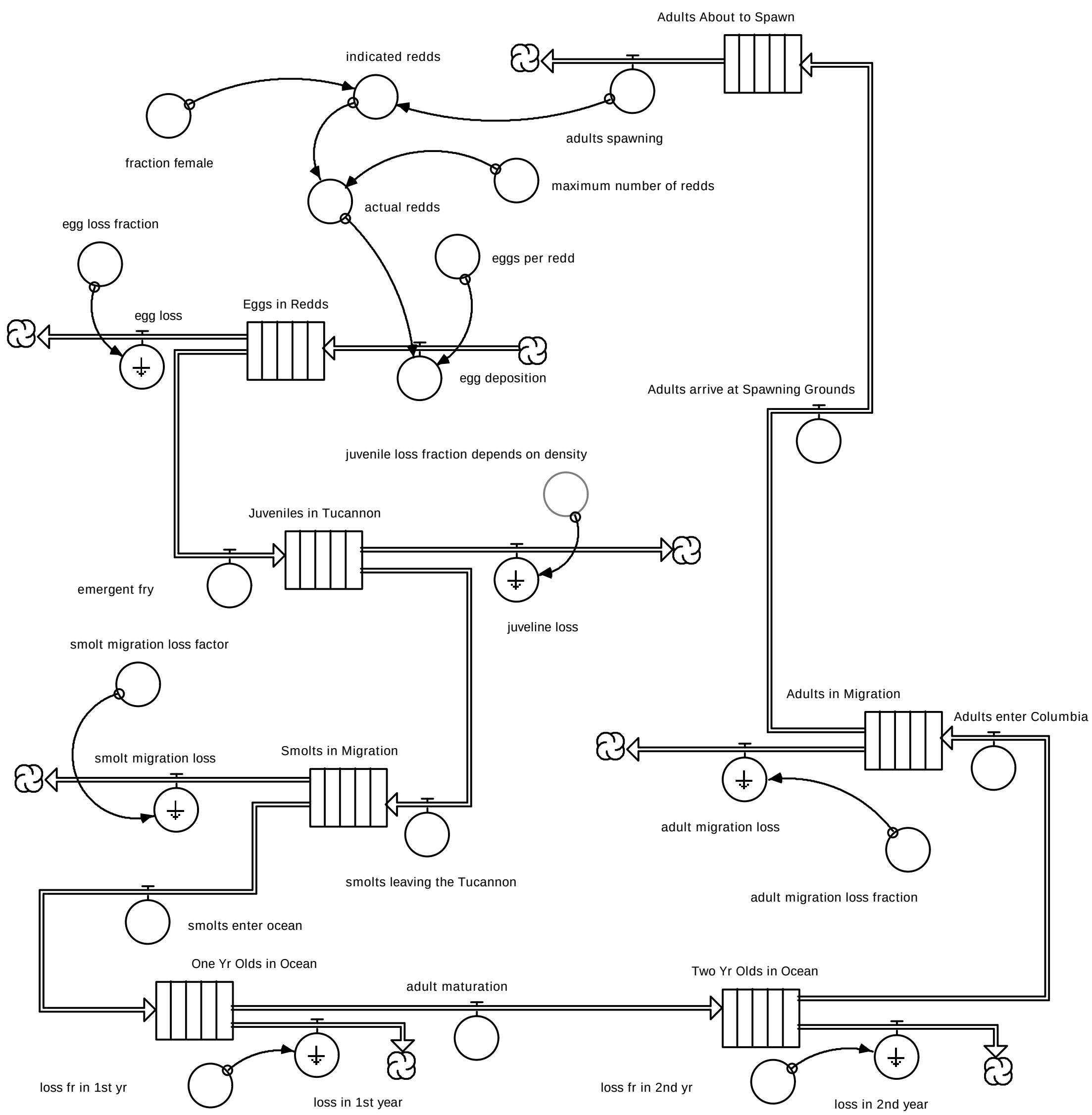


Figure 14.2. A model of the salmon life cycle.

The model uses seven population parameters which are assumed to remain constant over time. These are sometimes called "density independent" parameters because their values do not change with changes in the size of the population:

fraction female	50%
eggs per redd	3,900
egg loss fraction	50%
smolt migration loss factor	90%
loss fr for 1st yr	35%
loss fr for 2nd yr	10%
adult migration loss fraction	25%

The first three parameters match Bjornn's (1987) assumptions for the Tucannon under predevelopment conditions. The 50% female is typical of the Chinook salmon. Each female would deposit around 3,900 eggs and 50% of the eggs would survive with pristine conditions. The 25% adult migration loss fraction is taken from Bjornn's estimate of conditions prior to the hydro-electric development on the Snake and Columbia Rivers. The loss fraction during the smolt migration and the two loss fractions in the ocean were not available from Bjornn's analysis. These parameters are based on other sources and are combined so that the combination of losses is similar to the losses expected by Bjornn.

Let's place some of the assumptions in perspective by starting at the top of the diagram with 2,000 adults about to spawn. With 50% female, there would be 1,000 redds formed in the Tucannon. (You would see 20 redds if you walked a mile of the river.) With 3,900 eggs per redd, there would be 3.9 million eggs in the gravel nests. Half of these would survive to emerge as fry in the following spring. Now we have 1.95 million fry in the river. You'll learn shortly that only around 280 thousand of these juveniles will survive the first year in the river. These are the smolts that migrate to the ocean in the following spring. With 90% migration losses, 28 thousand reach the ocean.
And with 35% losses in the first year and 10% in the second year, around 16 thousand adults will return to the mouth of the Columbia two years later. The adult migration loss is expected to be 25%, so around 12 thousand adults will reach the spawning grounds. This calculation starts with 2 thousand spawners. Four years later, there are 12 thousand spawners. The annual growth rate is over 100%/yr! The conditions are certainly suitable for rapid growth in the population.

You know that no system grows forever, so it is logical to ask ourselves about the limits to the growth in the Tucannon population. One limit is the maximum number of redds that can be built in the river. At 65 redds/mile, the 50 miles of the Tucannon can support around 3,250 redds. This limit may be imposed by setting the maximum number of redds to 3,250 (which you may do in an exercise). For now, let's concentrate on a second limit which involves the carrying capacity of the river.

The Carrying Capacity

There are limits to the number of juveniles that can survive their first year in the Tucannon. During the summer, the juveniles must compete for a limited number of feeding sites. Later in the fall, they must compete for a limited amount of cover. Bjornn believes that summer conditions will constrain the size of the juvenile population, and he argues that juvenile survival is heavily dependent on density. Figure 14.3 shows a density dependent relationship between the number of surviving smolts and the number of emergent fry. The horizontal axis is the number of fry that emerge in the spring. The vertical axis is the number of juveniles that will still be in the river one year later ready to begin the smolt migration.

Figure 14.3 is highly nonlinear. We see a steep slope at the origin, but the curve is almost flat when the number of fry reaches 10 million. No matter how many fry emerge, there can never be more than 400,00 smolts one year later. The steep slope at the origin suggests that 1 million emergent fry would lead to over 200,000 smolts at the end of the year. We can obtain half of the river's carrying capacity with only one million fry. Further increases in the number of emergent fry do little to increase the number of smolts. If the fry were to increase from 5 to 10 million, for example, the surviving smolt population would only increase from around 340,000 to 370,000.

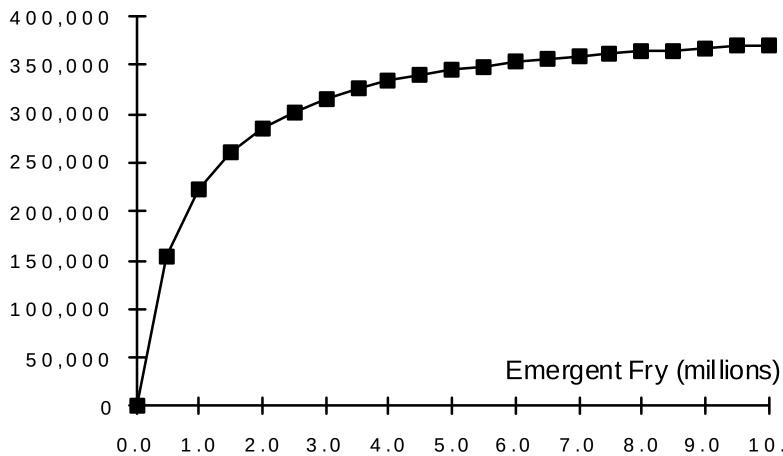


Figure 14.3 Number of juveniles expected to survive the first year of life in the Tucannon.

The shape of the nonlinear survival curve is based on the Beverton-Holt equation has been found useful in interpreting fish populations (Ricker 1975). The equation gives the number of surviving smolts as a simple function of the number of fry and two "curve fitting" parameters:

surviving smolts = Fry/{(Fry/CC) + (1/S)}

Bjornn recommends that CC, the carrying capacity, be set to 400,000 smolts. He recommends that S, the slope at the origin, be set to 0.5. The nonlinear relationship could be entered with a graph function (~), or we could enter the Beverton-Holt equation directly in the model. If we enter the equation, we will be in a better position to conduct sensitivity tests on parameters like CC, the carrying capacity. The relevant variable in Figure 14.2 is the shadowed variable *juvenile loss fraction depends on density:*

```
juvenile_loss_fraction_depends_on_density =
        (Fe-Expected_Smolt_Survival)/Max(1,Fe)
Expected_Smolt_Survival = Fe/((Fe/X4)+(1/X5))
X4 = Smolt_Carrying_Capacity
X5 = Fraction_of_Smolts_to_Survive_at_Very_Low_Density
Fraction_of_Smolts_to_Survive_at_Very_Low_Density = .5
Smolt_Carrying_Capacity = 400000
```

The short variable names (i.e., X4 and X5) match the terminology used by Bjornn (1987), and they allow the algebra to be clear. The longer names are used to communicate the meaning of each variable.

Simulation Results

The first test of the model is shown in Figure 14.4. The population is initialized at a low level and allowed to grow over time with all parameters held at pre development conditions. The time graph shows the simulated number of smolts migrating downstream and adults migrating upstream over a ten year period. Since the smolt migration lasts only one month, we see a series of ten spikes for each year of the simulation. The *smolts in migration* begins the simulation at around 100,000. (This starting value is the result of the initial value assigned to the stock of *Juveniles in Tucannon* at the start of the simulation.) The number of migrating smolts dips in the second year but increases strongly in the third year. Eventually, the number of smolts reaches around 380,000, and this number appears year after year. To check if we are observing S shaped growth, you might pencil in a smooth curve connecting the top of each spike in Figure 14.4. Your curve will reveal a four year cycle in the number of smolts. These oscillations are to be expected with an animal population with a four year life cycle. Figure 14.4 suggests that the oscillations will dampen out over time.

The second variable in Figure 14.4 is the number of adults migrating upstream. It begins the simulation at around 1,000. (This initial value is the result of the initial value assigned to the stock of *Two Yr Olds in Ocean*.) Recall that the adult migration lasts 4 months and that 25% of the adults do not survive the migration. Figure 14.4 reveals these losses as a downward slope associated with each of the ten migrations. If you pencil in a smooth curve connecting the peak number of adults, your curve will reveal a cycle in the number of migrating adults. Figure 14.4 shows that this oscillation also dampens out, and the number of adults levels off at around 22,000. This equilibrium value is approximately what we should expect based on the spread sheet calculations by Bjornn (1987).

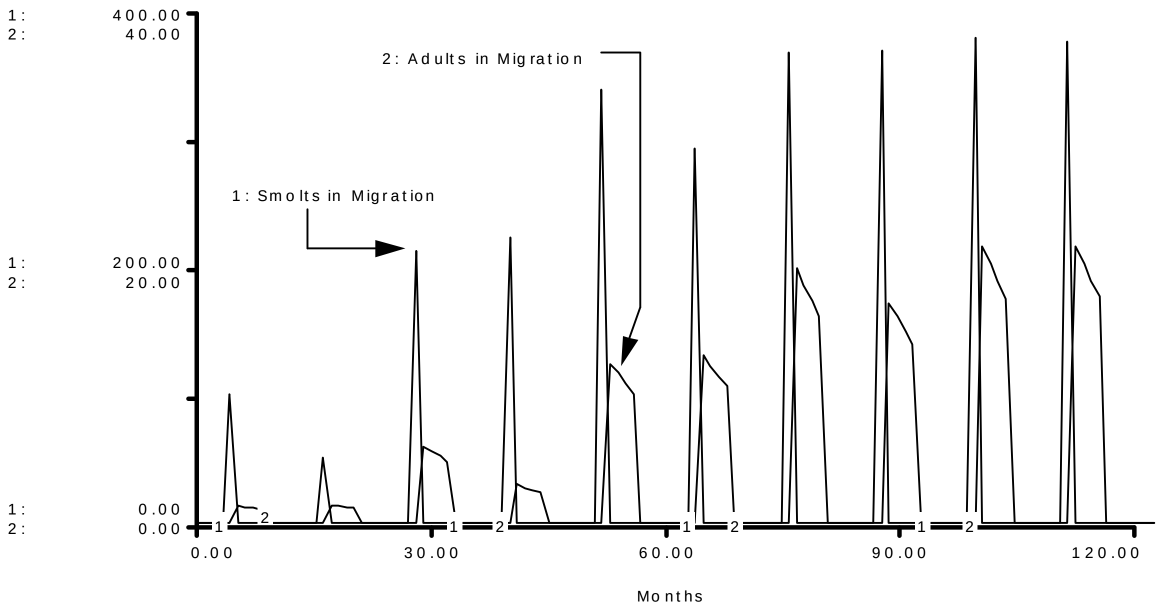


Figure 14.4. Simulated growth in the migrating populations under predevelopment conditions.

Equilibrium and Stability

You know from Chapter 5 that it's useful to check the numbers whenever a situation reaches equilibrium. This is normally done in an equilibrium diagram, but the salmon's complex life cycle makes it difficult to prepare a traditional equilibrium diagram. Nevertheless, we should be able to check the numbers to understand why the same number of adults return to the Columbia year after year. Let's start with the 22,000 adults which appears near the end of simulation. With 25% migration losses, around 16,500 will reach the spawning grounds, so there will be around 8 thousand redds and a total of around 30 million eggs. With 50% egg loss, around 15 million fry would emerge in the following spring. Their numbers would be "off the chart" in Figure 14.3. The number of juveniles to survive the year in the river would be around 380,000 thousand, just slightly less than the river's total carrying capacity. About 38,000 would survive the migration to the ocean. Ocean losses are 35% in the first year followed by 10% in the second year, so we would expect around 22,000 to return to the Columbia after two years at sea. We have equilibrium from one generation to the next.

You also know from Chapter 5 that it's useful to check the stability of an equilibrium situation by introducing an outside disturbance. Figure 14.5 reveals the general stability of the salmon model by introducing random disturbances in the smolt migration loss factor. The normal value of 90% applies for the first 120 months. Then the losses vary randomly from a low of 85% to a high of 95% for the remainder of the simulation. All other parameters are maintained at the same values used in the previous simulation. The test continues for 40 years to see the pattern in the number of adults.

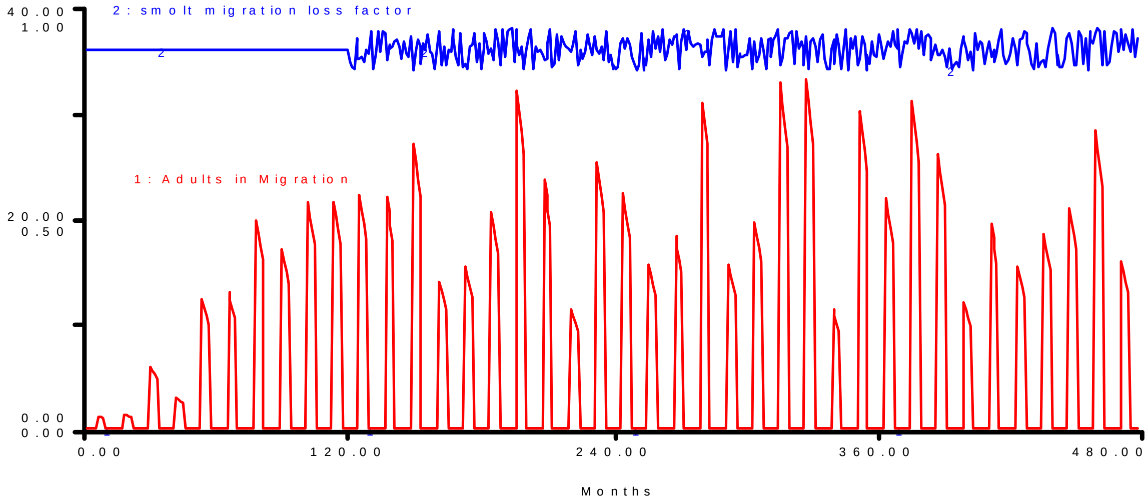


Figure 14.5. Test simulation with random variations in the smolt migration loss factor after the first 120 months.

This simple test reveals low runs of around 10,000 and high runs at over 30,000. We have a three fold variation in the number of returning adults due to random changes in just one of the model parameters. The test simulation also reveals a somewhat cyclical pattern to the variations. The cycles seem to match the four year life cycle of the salmon; you can check this match statistically as one of the exercises at the end of the chapter.

Feedback Structure

The salmon model exhibits S shaped growth over time, so we should expect to see a feedback loop structure similar to the flowered area and sales company described in Chapter 6. Specifically, we should expect to see at least one positive loop that gives the population the power to grow over time. There should be at least one decay loop that is similar to the decay of flowers. It will create constant losses in the system. And finally, there should be at least one negative feedback loop which acts to slow the rate of growth as the salmon fill up river. Figure 14.6 shows these loops and more.

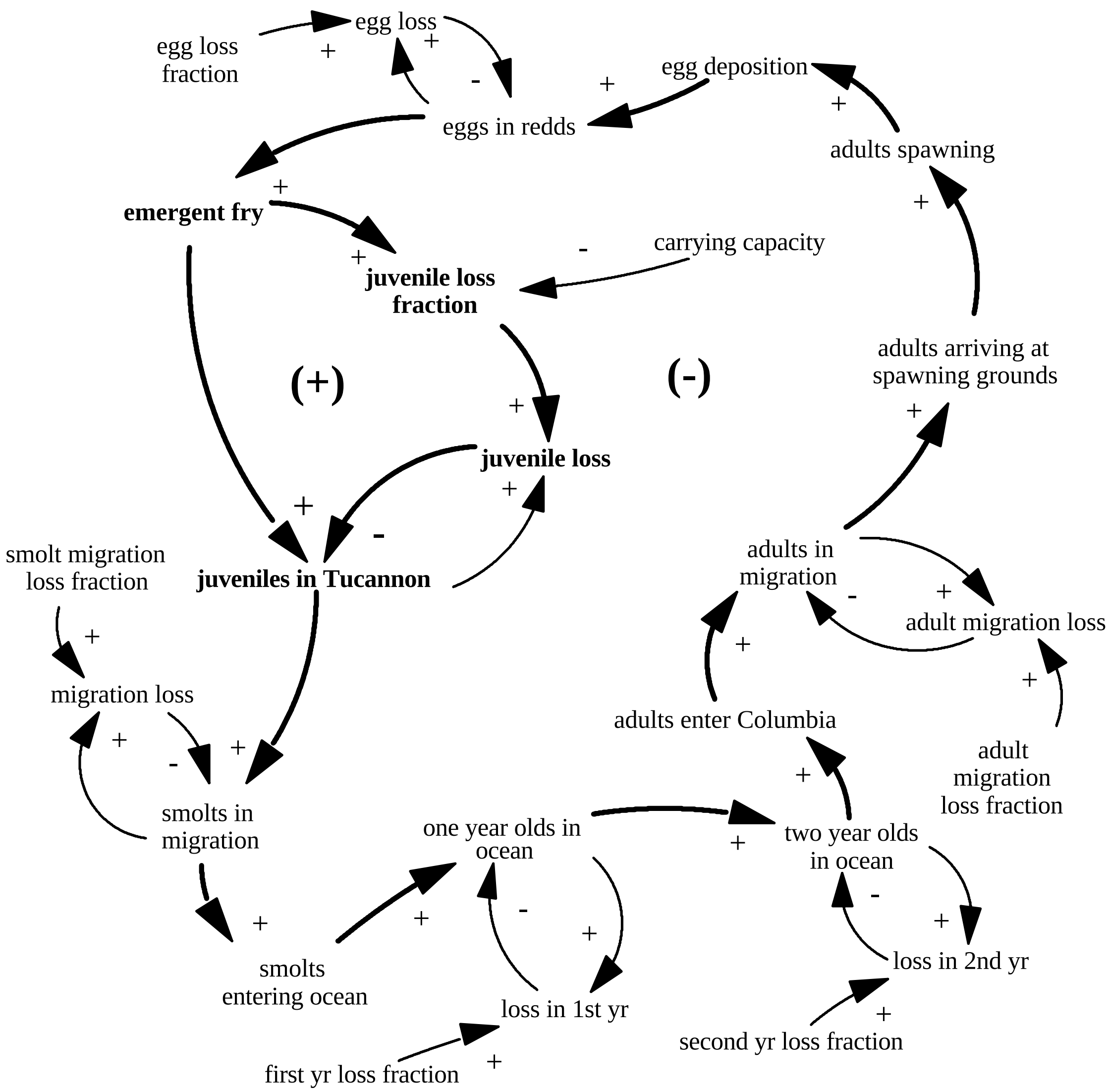


Figure 14.6. Information feedback in the salmon model.

The main positive feedback loop is highlighted by the darker arrows. We can follow their course around the perimeter of the causal loop diagram. If we start at the top with an increase in egg deposition, we will expect more fry, more juveniles, more smolts in migration, more salmon in the ocean, more adults entering the Columbia, more adults spawning and a subsequent increase in egg deposition.

Now do you see any examples of negative feedback loops that remind you of the flower decay loop? If you start at the bottom you will see a negative loop associated with the loss during the first year in the ocean. Moving to the right, you will see another negative loop involving losses during the second year in the ocean. And as you continue around the life cycle, you will see a total of six negative feedback loops. (Each loop involves only two variables, so the diagram doesn't include the (-) within each small loop.)

Now, turn your attention to the negative loop that is highlighted in Figure 14.6. It works its way around the entire life cycle, much like the positive feedback loop. If you begin at the top with higher egg deposition, we will see more fry, a greater juvenile loss, less juveniles in the Tucannon, fewer smolts in migration, fewer salmon in the ocean, fewer adults returning to spawn and less egg deposition in the future. This negative loop gradually applies the brakes to the growth. When would the growth eventually come to a stop? If you check the two sets of arrows leading from emergent fry to juveniles in the Tucannon, you would expect the system to slow down considerably when an increase in the emergent fry no longer leads to an increase in the number of juveniles. In other words, we would expect the system to grow until it reaches the flat portion of the nonlinear curve shown in Figure 14.3. Somewhere on the flat portion of the curve, the growth forces will be exactly balanced by the losses in the system

Harvesting

Let's expand the model to simulate harvesting of the adults as they enter the Columbia, as shown in Figure 14.7. A user specified harvest fraction is used to calculate the adult harvest and the number of adults that escape the harvest. The escaping adults then enter the conveyor for adults in migration to continue upriver as in the previous model. By specifying a fraction, we are assuming that the harvest manager knows how to measure the number of adults entering the Columbia in the current year.

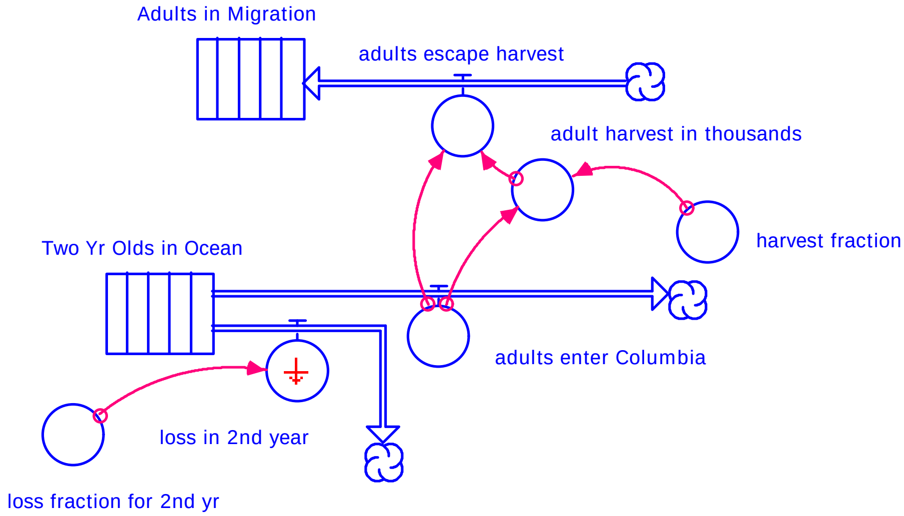


Figure 14.7. Adding the harvest fraction to the model.

The best way to test harvesting is to allow the salmon population to grow to its equilibrium size before any changes are made in the harvest fraction. Let's keep the harvest fraction at zero for the first ten years and then see what happens if we attempt to harvest 95% of the returning adults as they enter the Columbia. Figure 14.8 shows a 40 year simulation. The first 10 years are similar to the initial simulation -- the runs grow to exceed 20,000 per year. The harvest fraction is changed to 95% in the 120th month, so only around 1,000 adults escape the harvest. If you look closely at the spikes following immediately after the 120th month, you will see no change. The next four runs remain at over 20,000. The impact of the harvesting does not show up until four years later when the number of returning adults drops by almost 50%. We then see four successive runs of around 11,000 before the runs fall again. The declining pattern continues to follow this staircase pattern downward for the remainder of the simulation. This first test suggests that 95% harvesting is not sustainable.

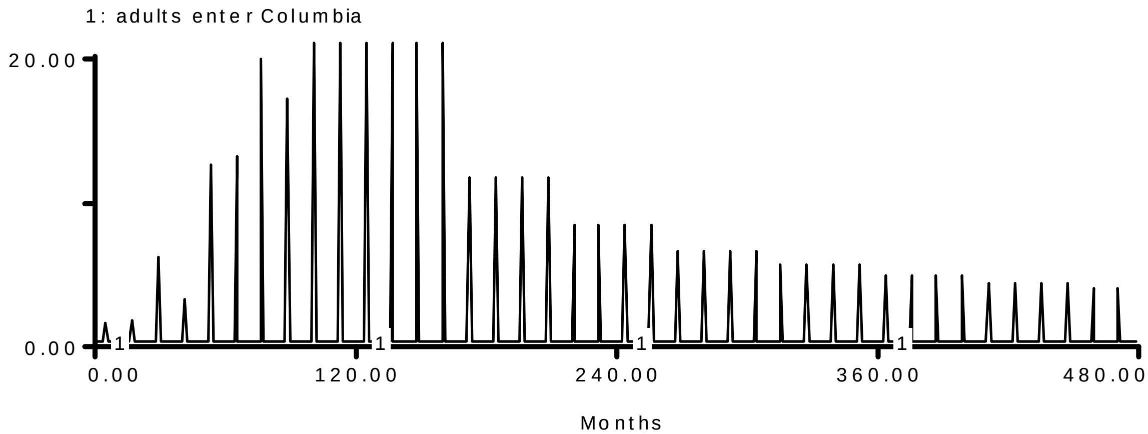


Figure 14.8. Testing 95% harvesting after the 120th month.

The next test allows the population to grow during the first 120 months as before. Then 50% of the adults are harvested for the remainder of the simulation. If you look closely at Figure 14.9, you will observe that there is no discernible impact on the number of adults that return each year. Their numbers continue at around 22,000 year after year even though 11,000 adults are harvested at the mouth of the Columbia. How can this possibly be?

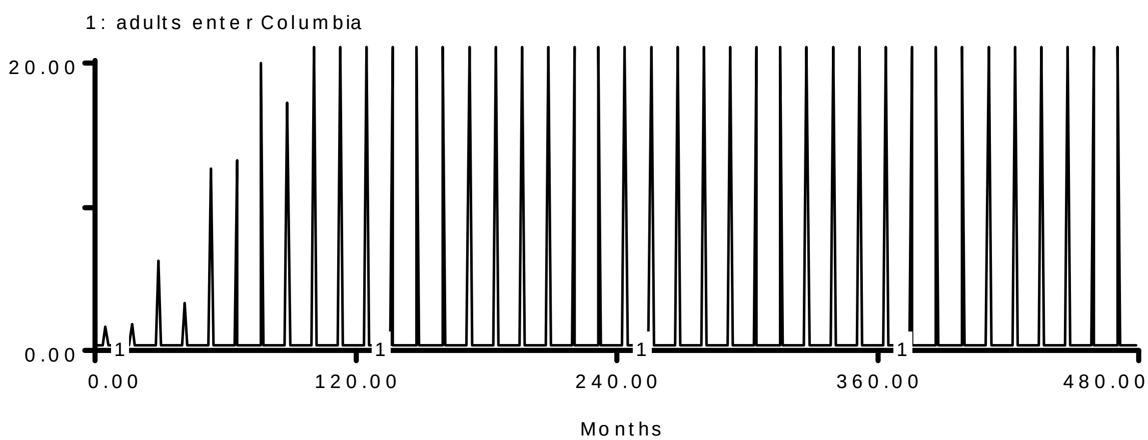


Figure 14.9. Simulated number of adults returning to the Columbia if 50% harvesting is begun in the 10th year.

The results in Figure 14.9 arise, in part, from the nonlinear shape of the juvenile survival curve. Recall the equilibrium conditions around the 120th month -- there were around 16,000 spawners, 8,000 redds, 30 million eggs and 15 million emergent fry. With 15 million fry emerging each year, the Tucannon is at its limit -- around 380,000 juveniles would survive their first year in the river. Now let's ask ourselves what would happen if 50% of the adults are harvested as they enter the Columbia. Half as many would escape so we would expect to see around 7.5 million emergent fry. According to Figure 14.3, the number of surviving juveniles with 7.5 million fry is almost identical to the number with 15 million fry. (The system is on the flat portion of the survival curve.) This simulation suggests that half of the adult population could be harvested without any visible impact on the number of adults that would return to the Columbia each year. This important result arises from the competition for space among the juveniles during their first year in the Tucannon. Harvesting cuts the number of escaping adults in half. But the progeny from the escaping adults will have a much greater chance of survival during their first year in the Tucannon.

Maximum Sustainable Yield

It is common practice in the study of fisheries to calculate the MSY, the maximum sustainable yield. MSY is defined by Botkin and Keller (1995, p. G-10) as “the maximum usable production of a biological resource that can be obtained in a specified time period.” Kenneth Watt (1968, p. 404) explains the search for MSY starting with minimal harvesting: “If we fish too little, the fish population left in the water after fishing will build up to densities at which intraspecific competition for food stunts fish growth and diminishes the probability of survival.” Then he explains that “if we fish too hard, too few adults are left behind to spawn, and the stock goes into a decline.” You can infer from the previous simulation that the 50% harvest fraction corresponds to “too little” fishing and the 95% corresponds to fishing “too hard.” Somewhere in between, we expect to find the maximum sustainable yield.

Figure 14.10 summarizes the results of five experiments with a constant harvest fraction imposed after the 120th month of the simulation. The 50% results from the previous figure are highlighed at the left edge of the diagram. The number of returning adults is just over 21,200 and the annual harvest is just over 10,600. When a similar test is conducted with 60% harvesting, the number of returning adults is almost 20,700 and the annual harvest is around 12,400. This result is also sustainable year after year. The experiment with 70% harvesting leads to a somewhat smaller number of returning adults. But since we are harvesting a larger fraction, the annual harvest turns out to be higher than in the previous experiments. The remaining two experiments allowed 80% and 90% harvesting. Both experiments revealed a sustainable situation. With 90% harvesting, for example, around 12,500 adults returned to the Columbia year after year. The annual harvest was around 11,240. This harvest was sustainable, but it turns out to be somewhat lower than the harvest observed in the experiment with 80% harvesting.

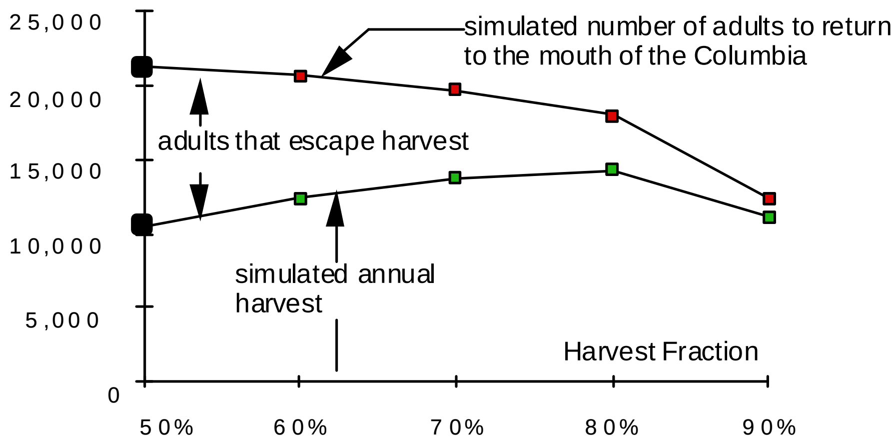


Figure 14.10. Results of five experiments with a constant harvest fraction after the 120th month of a simulation.

These experiments reveal an amazingly powerful system which will permit large annual harvests with a wide range of decisions on the harvest fraction. If we are asked to focus on the MSY, we would say that 80% would deliver an annual yield of over 14,000 salmon per year. If we were asked to recommend a policy to deliver at least 10,000 salmon per year, our job is easy. Set the harvest fraction anywhere from 50% to 90%, and the system will allow the goal to be met year after year.

Graphical Analysis

Traditional fishery studies often use graphical analysis to find the MSY. We have already found the maximum yield using multiple experiments with the Tucannon model, so we don’t need a graphical analysis. But since the graphical approach is common, it’s useful to illustrate the approach. The illustration will serve to reinforce the previous findings, and it will provide an example of the sort of analyses that is often conducted when managers do not have a dynamic model.

The graphical approach begins with the juvenile survival curve shown in Figure 14.11. Juvenile loss is the only loss in the model that depends on density. All other losses may be combined in a single line whose slope varies with changes in the harvesting fraction. Figure 14.11 demonstrates with four lines corresponding to harvest fractions of 0%, 50%, 75% and 90%. The fact that the straight lines intersect the survival curve is a sign that the harvest fraction is sustainable.

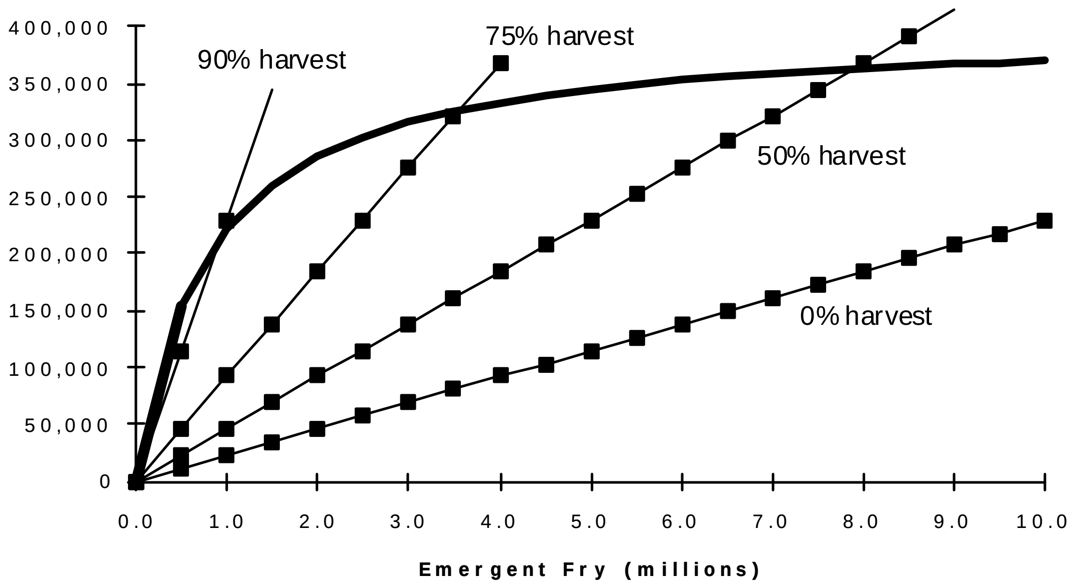


Figure 14.11. Graphical analysis of the number of smolts and fry in a sustainable system with different values of the harvest fraction.

To demonstrate, algebraically, why this is true, it is helpful to define the following terms:

h = harvest fraction	x1 = 25% adult migration loss fraction
A = Adults arrive at Columbia	x2 = 50% egg loss fraction
H = Harvest	x3 = 90% smolt migration loss fraction
F = emergent fry	x4 = 35% ocean loss fraction in 1st year
S = smolts ready to migrate	x5 = 10% ocean loss fraction in 2nd year
ff = 50% fraction female	epr = 3.9 thousand eggs per red

In a sustainable situation, we should expect to see:

$$F = A\,(1\text{-}h)\,(1\text{-}x1)\,(ff)\,(epr)\,(1\text{-}x2) = A\,(1\text{-}h)\,(.73)$$

This gives the fry, F, as a function of A, the number of adults. If we happen to know S, the number of smolts to begin the spring migration, we could find A:

$$A = S\,(1\text{-}x3)\,(1\text{-}x4)\,(1\text{-}x5) = S\,(.0585)$$

Now, insert the expression for A into the previous expression for F to obtain:

$$F = S\,(.0585)\,(1\text{-}h)\,(.73)$$
$$F = S\,(.0427)\,(1\text{-}h)$$

At this point, we have F as a linear function of S, but you can see from the graphical arrangement in Figure 14.11, that we need to express S as a linear function of F. This may be done as:

$$S = 23\,F/(1\text{-}h)$$

For any value of h, we can express S as a linear function of F. The lines in Figure 14.11 show four examples.

The purpose of the graphics is to find the intersection points. These points reveal the number of fry and the number of smolts that are consistent with all the assumptions of the model and with the assumption that the harvest is sustainable. With 50% harvesting, for example, the intersection point shows around 8 million fry and around 360,000 smolts. These values agree with the values found in the model in the experiment with 50% harvesting.

Now, to find the annual harvest, we set

H = hA,

and we express A as proportional to S using the previous expression:

A = S (.0585)

Now suppose we find S from the intersection points in Figure 14.11. We could calculate the annual harvest as:

H = .0585*h*S

Taking the three lines in Figure 14.11 as illustrative, we could eyeball the value of S to obtain rough approximations to the annual harvest.

h:	**S:**	**H=.0585*h*S**
50%	380,000	11,000
75%	330,000	14,000
90%	220,000	11,500

These values confirm the findings from the simulation experiments summarized in Figure 14.10. That is, the maximum sustainable yield is around 14,000. Moreover, it is possible to obtain yields of over 10,000 with harvest fractions ranging anywhere from 50% to 90%.

Graphical Analysis, Simulation Analysis and the MSY

The graphical approach provides a different perspective on the fishery, and it is encouraging to see the graphical results confirm the findings from the simulation model. But you might be wondering at this point why we should bother with the model? If we can find the maximum harvest graphically, why do we need computer simulation?

You should be aware of the highly restrictive assumptions that are required for the graphical approach to arrive at the intersection points. First, we must be willing to assume that the system is predominantly linear. In the case of Figure 14.11, we are willing to tolerate a nonlinear relationship for the smolt survival curve, but all other relationships are linear. If some of the remaining relationships were nonlinear, you can imagine the complexities in finding the intersection points. In simulation modeling, on the other hand, we are free to consider each relationship separately. If a linear representation seems more realistic, we can simply employ a graph function (~) and repeat the simulation.

A second restriction in the graphical approach is the assumption that the system is operating in a sustainable manner. For the algebra underlying Figure 14.11 to make sense, we must assume that the same number of fish appear in the system from one generation to another. This assumption is suitable in searching for the MSY, but it certainly restricts our ability to analyze a broad range of situations (such as the oscillating situation in Figure 14.5).

Now, what about the MSY? The MSY is emphasized by Bjornn (1987), and it certainly appears frequently in the literature. Indeed, the idea was considered “virtually sacred to many wildlife managers until quite recently” (Botkin and Keller 1995, p. 232). But you should regard the MSY with great skepticism since it is an artificially determined number. To appreciate the artificiality, think of the unusual conditions that were created in the simulation experiments to find the MSY. Each experiment held the values of all parameters constant over time at values representing predevelopment conditions. There were no random disturbances, and the harvest fraction was implemented once the population reached equilibrium. We then held the harvest fraction constant for thirty years and recorded the simulated response. This was done not once, but five times. The results are reported in Figure 14.10; they indicate that the MSY is around 14,000 and it could be obtained with a harvest fraction of around 80%.

You shouldn’t pay too much attention to these two numbers. The important conclusion from of the preceding analysis is not the 80% or the 14,000. What we really learn from the previous simulations is that the predevelopment conditions allow for a wonderfully powerful and stable system. We have learned that the Tucannon salmon system could allow for major harvests that could be sustained year after year if we set the harvest fraction anywhere from 50% to 90% and if we maintain the rivers and the habitat in good condition.

The Impact of Development

Bjornn was primarily interested in land use development which has lowered the quality of the salmon habitat. An example is the heavy erosion from dry cropland and cattle grazing that dumps sediments into the Tucannon (Harrison 1992). Bjornn suggests that the impact of land use may be simulated by changing the egg loss fraction and the carrying capacity. Egg loss increases as sediment ruins the quality of the gravel beds. Bjornn suggests increasing the loss from 50% to 75% to represent the deterioration of water quality. Land use has also degraded the habitat that the juveniles will experience after hatching. Bjornn suggests that degradation in the lower sections of the river can be representing by lowering the carrying capacity from 400,000 to 170,000. Development has brought important changes in the large rivers as well. Hydroelectric development on the Snake and the Columbia has placed 6 dams and reservoirs between the smolts and the ocean. Bjornn suggests that the impact of hydro-electric development may be represented by increasing the smolt migration loss fraction from 90% to 95% and the adult migration loss fraction from 25% to 37.5%.

Figure 14.12 shows the simulated number of returning adults if all four of these changes are implemented after the 120th month of a simulation. The first ten years appears as in each of the previous simulations. The population is allowed to grow to the equilibrium value of 22,000. The impact of development is abrupt and dramatic. The number of returning adults declines within a few generations to around less than 20% of the predevelopment population. The population is simulated to find a new equilibrium and remain stable at slightly below 4,000

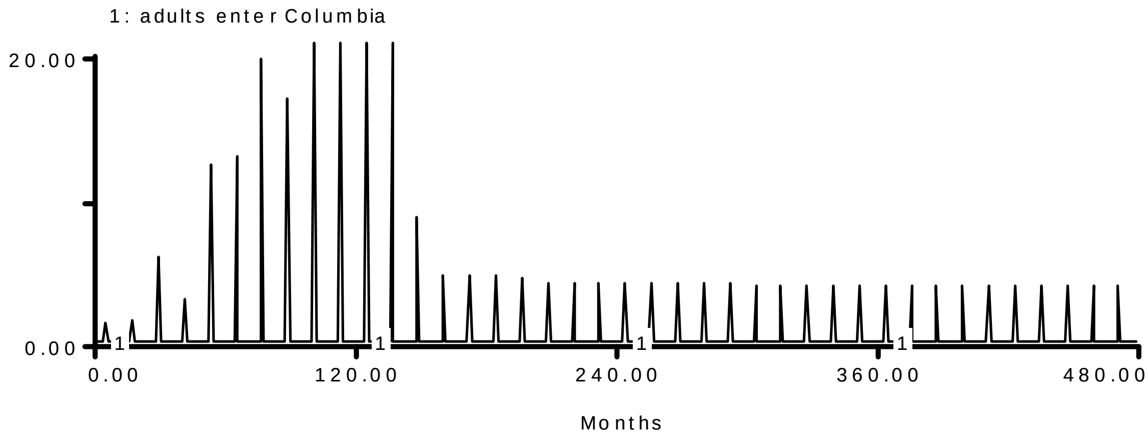


Figure 14.12. Simulated Impact of Land Use Changes and Hydro-electric System Development starting in the 120th month of the simulation.

At this point, one may experiment with different harvesting policies to learn if the post development salmon population could be harvested in a sustainable manner. For example, 25% harvesting begun after the salmon reach the post development equilibrium could deliver a sustainable harvest of around 900 fish per year. You may try alternative harvest fractions to find the MSY under developed conditions as an exercise at the end of the chapter. You'll learn that the harvest is nowhere close to the harvests that were possible with predevelopment conditions.

Summary

This chapter describes a system dynamics model of the salmon population in a small river in southeastern Washington. The model simulates the salmon's complex life cycle, and it has been used to test the impact of land use development, hydro-electric development and harvesting. The model may certainly be improved, as you will be challenged to do in the exercises at the end of the chapter. The exercises also allow you to experiment with the model while assuming the role of fishery manager. To appreciate the relevance of the Tucannon example to other systems, it's useful to review the state of fisheries around the world.

The World's Fisheries

The decline in the Tucannon salmon parallels the overall decline in the salmon and steelhead populations of in the northwest. Unfortunately, the northwest salmon fishery is not unique. Clark (1985, p. 5) observes that the "depletion of major fish stocks and the impoverishment of fishing fleets and processing companies have become common phenomena worldwide." Clark comments that several major fisheries have collapsed completely, largely as a result of overfishing. For example:

- Antarctic blue whales and fin whales showed peak catches of around 30,000 in the 1930s; by 1981, the catch in both fisheries was nil.

- Peruvian anchoveta supported a peak catch of over 12 million tons in 1970; by 1981, the catch was only 0.3 million tons.

- California sardine supported a catch of over 600,000 tons in 1936; by 1981 the catch was nil.

Clark believes that fisheries biologists are well aware that many fish populations undergo large scale natural fluctuations. But the development of a commercial fishery may be "first precipitated when a population is at a peak of abundance. If the stock subsequently declines, it may be difficult to disentangle the influences of fishing pressure and natural processes." He concludes that it has become clear "that the uncontrolled growth of a large fishing industry has the potential for hastening and exacerbating the decline, as well as preventing the recovery of such stocks" (Clark 1985, p. 6)

Clark's commentary raises the question of how to prevent "uncontrolled growth" of a large fishing industry. We might look to market forces to slow the growth of the industry. We could reason that lower catches will discourage new entry; existing fishermen will switch to a different vocation; and the stocks might recover over time. But the evidence from one fishery after another suggests that the markets don't provide the controls needed to prevent overfishing:

> *The fishing industry around the world enjoys fairly free and vigorous markets, and it has seen in the past few decades extraordinary technological development...The result is that more and more fisheries are overshooting their sustainable limits. The technology being called forth is not that which enhances fish stocks, but that which seeks to catch every last fish.*
>
> (Meadows 1992, p. 186)

As the companies succeed in catching the last few fish, they find themselves left with excessive capacity. One example is the Pacific Northwest salmon fishery studied by Paulik and Greenough (1966). It was described as heavily overinvested in the "gear" needed to catch salmon (Watt 1968). In writing about fisheries in general, Clark (1985, p. 7) explains that "in practice .. it often appears that the effort capacity of fishing fleets is much larger than twice the optimum level."

Computer simulation can help us think about the many interacting forces that pose such difficult problems in fisheries. At a basic level, a model may trigger a fundamental change in thinking as when a company decides to change its goal from catching more fish to catching fewer fish. A model may also be used to help participants in a fishery work through the challenges of survival if they commit to lowering the annual catch. The salmon gear modeling of Paulik and Greenough (1966) is an interesting example from the 1960s. Two recent examples are the Fish Banks Ltd. and the Norwegian fjord experiment. Both examples are exemplary for their use of models within a learning exercise.

Lessons from Fish Banks, Ltd.

The first example is Meadows' (1989) "Fish Banks, Ltd." simulation game. The model simulates the interactions of a hypothetical fishing fleet and fish populations in coastal waters and in deep waters. Teams of participants are formed to represent fishing companies. Each team is free to experiment with different policies to grow their fleets and to achieve a high, sustainable income. The game has been played by resource planners and students from around the world. The results are similar for students and planners alike. They tend to overinvest in the number of boats. Then they operate the boats to the point where the fish populations are depleted. The depletion tends to occur first in the deep sea, then in the coastal waters.

Participants in the Fish Banks exercises argue that it was not possible for them to avoid overfishing, even when they feared that their actions were depleting the stock. They faced the fundamental challenge of a "common" resource. They knew that the combined actions of all the teams were depleting the fishery, but they did not want to be the only team to cut back on fishing. Their reactions were similar to the reaction of an American fisherman working the Bristol Bay salmon fishery in Alaska . According to (Howe 1979, p. 272), the American fisherman knew he was simply one player in a system that was headed in a tragic direction. When asked it the fishing season should be closed, he responded:

> *Why should they close it if the Japanese are going to be out there? I'd just as soon wreck it ourselves as have them wreck it.*

This fundamental and tragic problem is called the "Tragedy of the Commons" (Gordon 1954, Hardin 1968). The main source of the problem is often attributed to open access to the stocks. Howe (1979, p. 257) explains that "where resources are unowned or the common property of a community, "there are no controls over access and no means of allocating or restricting inputs of capital and labor." Under these conditions, there is simply no way to prevent "declining yields and the disappearance of net revenues to the industry."

Lessons from the Norwegian Fjord Experiment

The second exemplary example is the Norwegian fjord experiment by Erling Moxnes. Moxnes recruited 83 subjects from the fishery sector in Norway to conduct harvesting experiments with a simulated cod population in an isolated fjord. His subjects were granted exclusive property rights, so each participant was free to make decisions about the size and the use of their fleet without fear that a competitor would deplete the cod population. In other words, his experiment ruled out the "commons" problem which is at the heart of Fish Banks Ltd. Moxnes' findings are intriguing -- the participants consistently overbuilt their fleets. For example, a typical participant would buy 5 boats to work the fjord when 3 boats would deliver the maximum sustainable yield. Each of participants had exclusive rights to the simulated fishery, so they were free to "lay-up" their boats when they discovered their overinvestment. To their credit, they managed to idle their boats and avoid decimating the fishery. Moxnes (1996, p. 23) observes that the subjects' responses are quite similar to the Norwegian fishing situation where capacity has been estimated to be about twice the optimal size for the past fifteen years. Moxnes believes that quotas in Norway have probably have been closer to optimal levels.

At this point, you might be wondering why the Norwegian participants overinvested in their fishing fleets. Moxnes reports that the information was available for them to determine the maximum sustainable harvest. But somehow, they didn't see it. Moxnes describes their inability to see the situation properly as a "misperception of feedback."

Misperception of feedback is a general term coined by Sterman (1989) to explain poor performance by participants in complex systems in general and in carefully controlled management experiments. The term is often taken as
"shorthand" for a combination of system features that seem to be beyond our ability to understand. One feature is nonlinearity, like the highly nonlinear juvenile survival curve discussed in this chapter. Another feature is delays, like the four year delay before changes in harvesting show up as possible changes in the number of returning adults. Finally, and most importantly, "misperception of feedback" refers to our apparent inability to "see" the feedback at work in the system. To illustrate what Sterman has concluded from management experiments, imagine a scene from ordinary life. Imagine that a visitor arrives at your house to find that it is terribly overheated. (You love a warm room and you've set the thermostat at 90 degrees.) Your visitor arrives to find you gone and the house unbearably hot. What might he do if he did not appreciate the feedback control of the furnace through the thermostat? He might launch into a series of wasteful activities to correct the problem. He could open the windows to let cool air into the house. And when that didn't work, he might open the refrigerator door to let cool air out of the freezer. Of course, you recognize immediately that these actions will not succeed. But that's because you do not suffer from "misperception of feedback."

The Role of System Dynamics

System dynamics models can play the same role in fisheries management as they play in other complex systems -- they help us to "see the feedback" at work in the system. Their main benefit is likely to be an improved understanding of dynamic behavior and better instincts for managing the system. They may be constructed for extended analysis by a team of managers and experts, or they may be designed for workshops and training as in the examples of Fish Banks, Ltd. and the Norwegian fjord experiment.

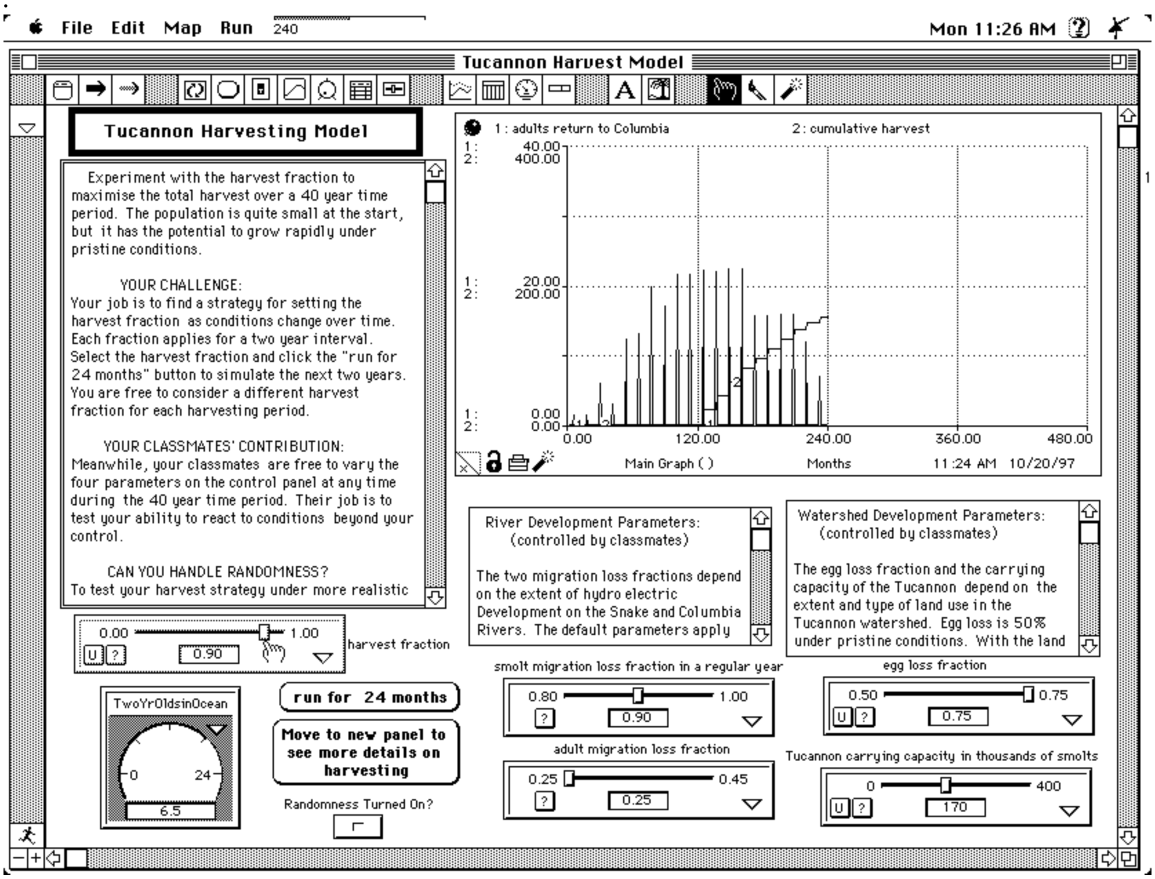
Exercises

The first exercise calls upon you to experiment with a highly interactive version of the Tucannon model. Such models are sometimes called "management flight simulators." You learn more about their purpose in Chapter 20. For now, you may download the Tucannon Harvest model for the first exercise. The remaining exercises are similar to exercises in the previous chapter. They call on you to verify, apply and improve the model.

1. Tucannon Harvest Exercise

The harvest exercise is a game for three. You will assume the role of harvest manager. One classmate assumes control of hydro-electric development. The other assumes control of land use in the watershed. Your job is to find a strategy for setting the harvest fraction as conditions change over time. Meanwhile, your classmates will be changing the simulated conditions. Their job is to test your ability to react to conditions beyond your control.

The “screen capture” shows the monitor of a Macintosh computer midway through a student experiment with the harvesting model. Instructions are given in the scrolling field on the left side of the screen. You are to experiment with the harvest fraction to maximize the total harvest over a 40 year period. In this screen, the classmates have raised the egg loss fraction



and lowered the carrying capacity. You can imagine that their goal was to create a challenging situation for the harvest manager. Results for the first 240 months are on display in the main graph, and the “finger” is pointed at the harvest fraction which is currently at 90%. The harvest manager is probably wondering whether to change the fraction before advancing through another 24 months of the simulation.

Experiment with the interactive model until you feel that you have demonstrated your ability to manage the system. Conduct a final simulation that reveals your ability to manage the system under challenging conditions. Document the results of the final simulation with the “Print Map” command.

2. Verify

Use the downloaded model to verify the simulation results in Figure 14.4.

3. MSY Check
Confirm the 50% harvesting result shown in Figure 14.9. Then select a harvesting fraction between 50% and 90% and run the model to see if the simulated harvest matches what you would expect from Figure 14.10.

4. Relative Losses
The Tucannon model sets the smolt migration loss at 90% and the ocean losses at 35% in the first year and 10% in the second year. Based on discussion with Ted Bjornn, the smolt loss fraction could be reduced and the ocean losses increased. Conduct a test with the smolt migration loss fraction at 50% and the ocean losses set at 75% and 50%. How does the new simulation compare with the simulation in the 2nd exercise?

5. Verify Stability Check
Use the model to verify the stability check in Figure 14.5. (Caution: your random variations in the smolt migration loss fraction may not match exactly the sequence used in Figure 14.5, so you should not expect to match each and every variation.)

6. 90% Harvesting with Random Disturbances

Introduce 90% harvesting midway through the previous simulation to learn if 90% harvesting is sustainable when the system is subjected to random disturbances.

7. Verify Developed Conditions
Use the model to verify the simulated impact of development shown in Figure 14.12. Then conduct an additional experiment with 25% harvesting starting in the 240th month of the simulation. You should see annual returns of 3,490 returns and an annual harvest of 870. Can you do better with a higher harvest fraction?

8. Limit on the Number of Redds
The *indicated redds* in Figure 14.2 is the product of the *adults spawning* and the *fraction female*. The *actual redds* takes the value of the *indicated redds* or the *maximum number of redds,* whichever is smaller. Set the *maximum number of redds* to 3.27 to represent Bjornn's estimate that the Tucannon could support 3,270 redds. Run the model to learn if this limit leads to any changes in the results in Figure 14.4.

9. Time Series Analysis

If you have studied time series analysis, you will have learned about the stationary, autoregressive model to explain the variation in population numbers based on variations one year ago, two years ago, three years ago, etc. Repeat the simulation from the 5th exercise and ask for a table of results. You might imagine that the table of results is similar to time series data that might be collected on the returning adults. But since these results are created by a model, they might be called *synthetic data.* If you have access to a statistical analysis program, export results to the statistical program. Create a stationary, autoregressive model, and run the program to estimate the coefficients from the synthetic data. Does your analysis reveal a four year lag in the salmon population?

10. Precocious Fish

Draw a new version of the flow diagram in Figure 14.2 to include the possibility that some salmon return to the Columbia after only one year in the ocean. These are precocious fish, so name these fish "precos" in the model. Introduce a new converter called *Fraction Precos* as an input. Except for their early return, the precos have the same biological properties as the regular fish.

11. Precocious Fish, Part II

Draw a new version of the flow diagram to add the precocious fish to the model. But in this case, you are told that the precocious fish have a higher *adult migration loss factor* and a smaller number of *eggs per redd*..

12. Third Year in the Ocean

Draw a new version of the flow diagram in Figure 14.2 if you are told that the salmon spend three years in the ocean rather than two. The total life cycle is now five years rather than four. Suppose all other population parameters were the same as the previous model, and suppose the loss fraction during the 3rd in the ocean is negligible. Would the new model reach a dynamic equilibrium? If so, would the equilibrium value of the number of returning adults be higher or lower than the previous model?

13. Simulate the Third Year

Build the model diagrammed in the previous exercise and use it to check your reasoning about the size of the equilibrium population.

14. Combine the Salmon Models?

The model in Chapter 13 provides a detailed simulation of hatchery smolts during their spring migration. Do you think it would be useful to combine the model from Chapter 13 with the life cycle model in this chapter? If the DT is set to 1 day (as in Chapter 13), how many steps would be needed to run the new model to compare to Figure 14.12?

Further Reading

1. The Tucannon basin is home to around 800 people. Harrison (1992) describes their efforts to improve farming methods and salmon habitat.

2. The world's imperiled fisheries are described by Safina (1995).

3. More information on graphical analyses in fisheries studies is given by (Bjornn 1987, p. 25; Paulik and Greenough 1966, p. 225; Clark 1985, p. 4).

4. Botkin and Keller (1995, p. 234) explain the dangers of linking harvest policy too closely to a predetermined MSY, especially if the MSY is derived from a "logistic model" of the animal population.

5. Larkin (1988) discusses the relative advantages of simulation modeling versus analytical solutions in fishery management. He believes "there is virtually no limit to the variety of and complexity of simulations" and he argues that simulation models should be viewed as "tools to assist the imagination."

References

1. Harrison, John. 1992. Tackling the Tucannon. *Northwest Energy News* March-April. (Northwest Power Planning Council, 851SW Sixth Avenue, Portland, OR 97204).
2. Safina, Carl. 1995. The world's imperiled fish.*Scientific American* (November): 46-53.
3. Bjornn, T.C. 1987. A model for predicting production and yield of Tucannon River salmon and steelhead stocks in relation to land management practices. Techical Report 98-1 of Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, ID 83843.
4. Paulik, G., and Greenough, J. 1966. Management Analysis for a salmon research system. In *Systems analysis in ecology*, edited by Kenneth Watt. New Yourk: Academic Press.
5. Clark, Colin. 1985. *Bioeconomic modelling and fisheries management*. New York: John Wiley.
6. Botkin, Daniel, and Keller, Edward. 1995. *Environmental Science*. . New York: John Wiley.
7. Larkin, P.A. 1988. Pacific salmon. Chap. 7 in *Fish population dynamics*, 2nd ed., edited by J.A. Gullard. . New York: John Wiley.